APPLICATIONS OF QUANTUM INFORMATION TO QUANTUM GRAVITY, BLACK HOLES, & QFT

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The Roles of QIS in HEP
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QUANTUM INFO IN QFT: MOTIVATION

- QFT: lingua franca of the high energy world built on principles of quantum mechanics & relativistic invariance with amazing predictions and applications, from SM of particle physics to inflationary cosmology.

- Formalism is not explicitly geared towards exploiting quantumness of quantum mechanics. Still information to be mined.

- Composite quantum mechanical systems exist in tensor product superpositions, with combined unitary evolution of entire system, but not so for any subpart. Subsystems evolve non-unitarily generically.

The best possible knowledge of a whole does not necessarily include the best possible knowledge of all its parts, even though they may be entirely separate and therefore virtually capable of being 'best possibly known', i.e., of possessing, each of them, a representative of its own. The lack of knowledge is by no means due to the interaction being insufficiently known at least not in the way that it could possibly be known more completely it is due to the interaction itself.

E. Schrödinger (1935)

QUANTUM INFO BEYOND QFT: MOTIVATION

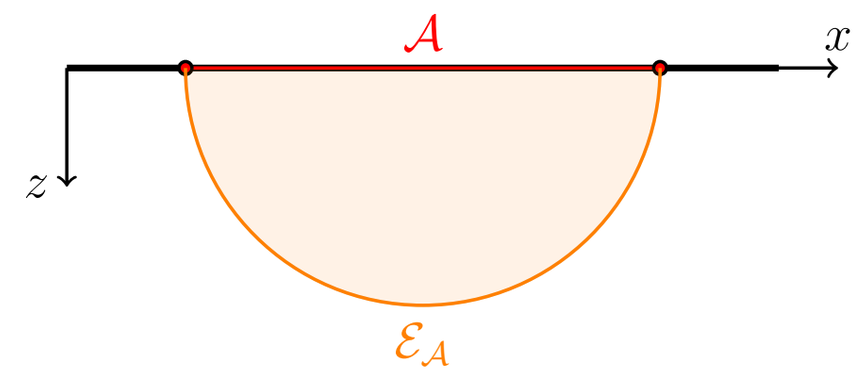
- Lossy evolution of subparts characterized by information theoretic measures: von Neumann (entanglement) entropies and suchlike.

- Pertains to all quantum systems but is most striking in applications to black hole information problem.

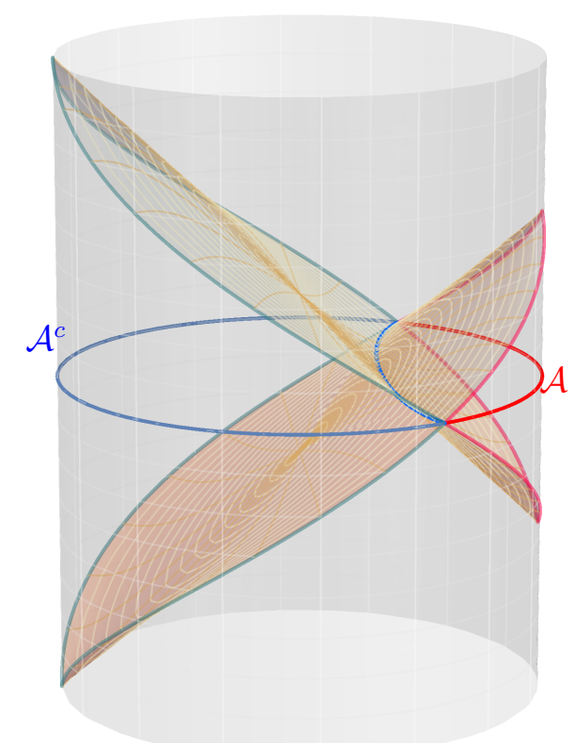
- Notable developments of the past 3 decades:
  - sub-extensive nature of von Neumann entropy
  - the holographic nature of gravity
  - AdS/CFT correspondence
  - geometrization of entanglement measures in holography
  - holographic map as a quantum error correcting code
  - a semi-classical resolution of black hole information problem

ENTANGLEMENT AND GEOMETRY

- Quantum gravity in an asymptotically AdS spacetime is dual to a non-gravitational quantum field theory. As complete quantum theories the two are identical, and have isomorphic Hilbert spaces.



- Holographic EE proposals relate entanglement entropy of field theory to areas of extremal surfaces in the geometry.

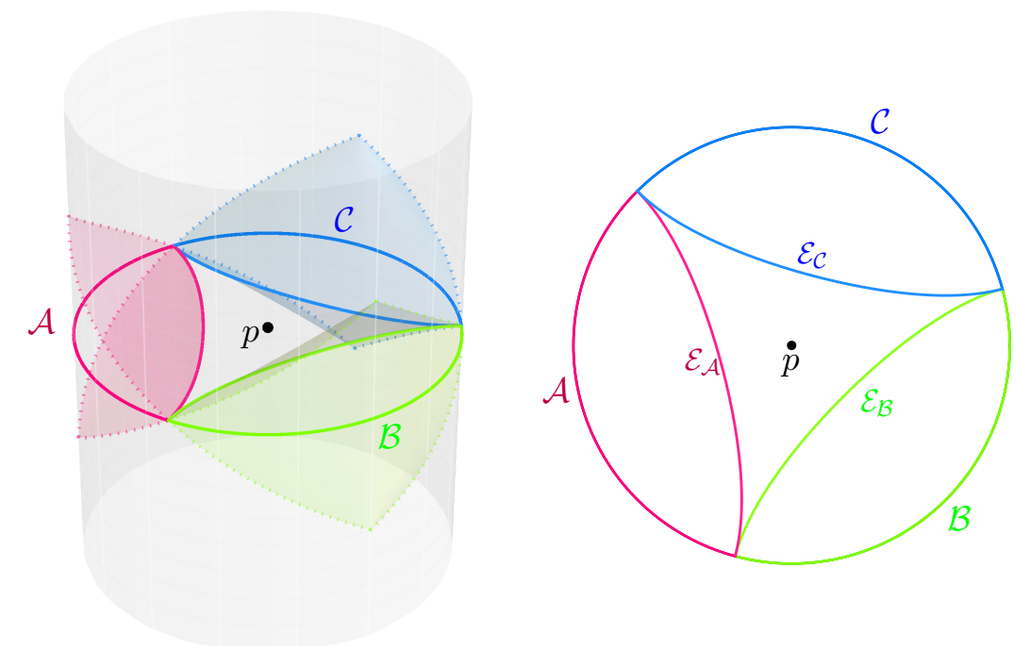


- Including quantum corrections, one finds a certain optimization problem in the gravitation setting: the quantum extremal surface prescription, optimizes a gravitational entropy (which includes the area as leading contribution).

HOLOGRAPHIC MAP AS ERROR CORRECTION

- How does one reconstruct gravitational data, i.e., recover geometry as we know it?

- Semi-classical gravity Hilbert space is smaller than the full quantum gravity Hilbert space – this is embedded into the dual QFT Hilbert space.

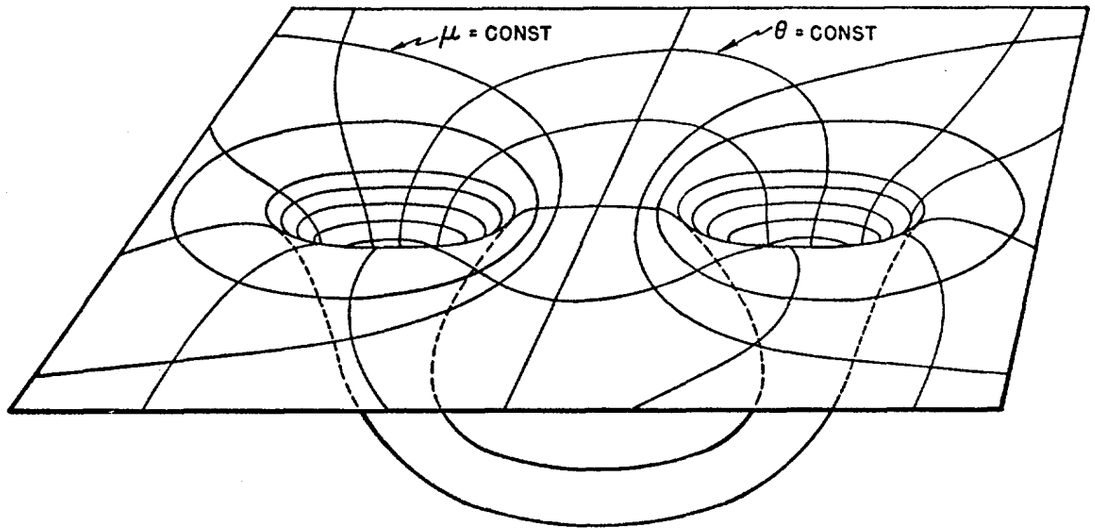


- The holographic encoding of geometry is analogous to quantum error correcting maps.

- Very well understood in tensor network models of holography (see Brian Swingle's talk).

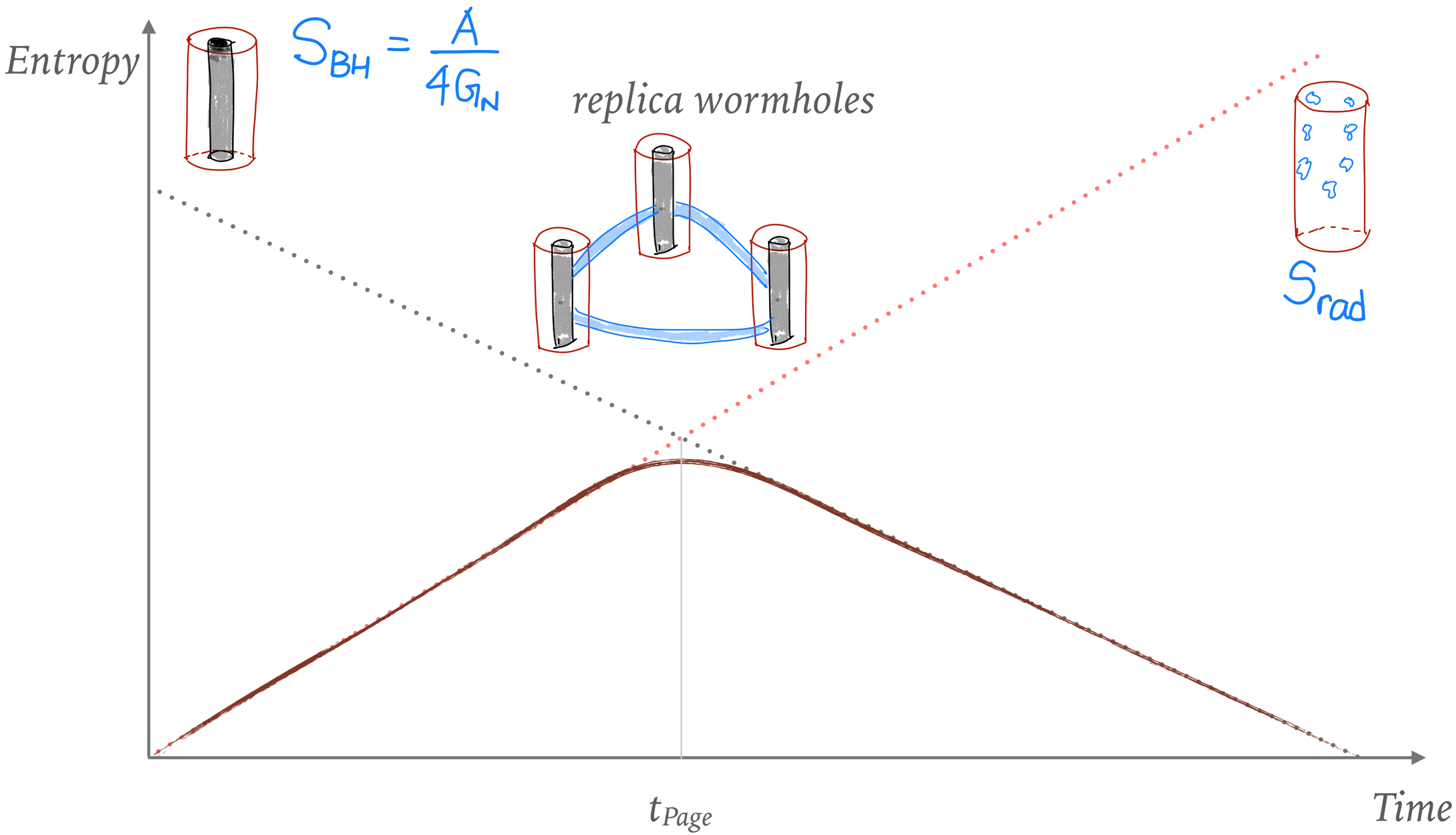
TELEPORTATION AND WORMHOLES

- Opens up exciting prospects for understanding and constructing new communication protocols in QFTs, which is tantamount to building spatial wormholes in gravity.



- Starting with a suitably entangled state of QFTs one can set up a teleportation protocol that geometrically constructs such wormholes in gravity.
- Ongoing efforts to understand the feasibility of constructing traversable wormholes with Standard Model matter.
- Prospects for realizing such constructions in the lab using low dimensional quantum mechanical avatars of holography (eg., SYK model).

BLACK HOLE INFORMATION 2020



BLACK HOLE INFORMATION: REPLICA WORMHOLES

- Recovery of the Page curve from new semiclassical configurations is a remarkable development.
- Specific configurations that lead to the answer however are exotic spacetime (replica) wormholes, wherein different universes get connected through non-trivial topology.
- Raises important questions about the nature of quantum gravity and information:
  - Dynamical process whereby the new geometries take over the real-time evolution is yet to be fully understood (analogy with tunneling solutions).
  - Suggests qualitative difference between tracing out and random projections, which could be interesting to explore information theoretically.

EVOLUTION OF INFORMATION

- Classically black holes are efficient processors of information, giving striking bounds on quantum information processing rates when translated to the dual field theory.

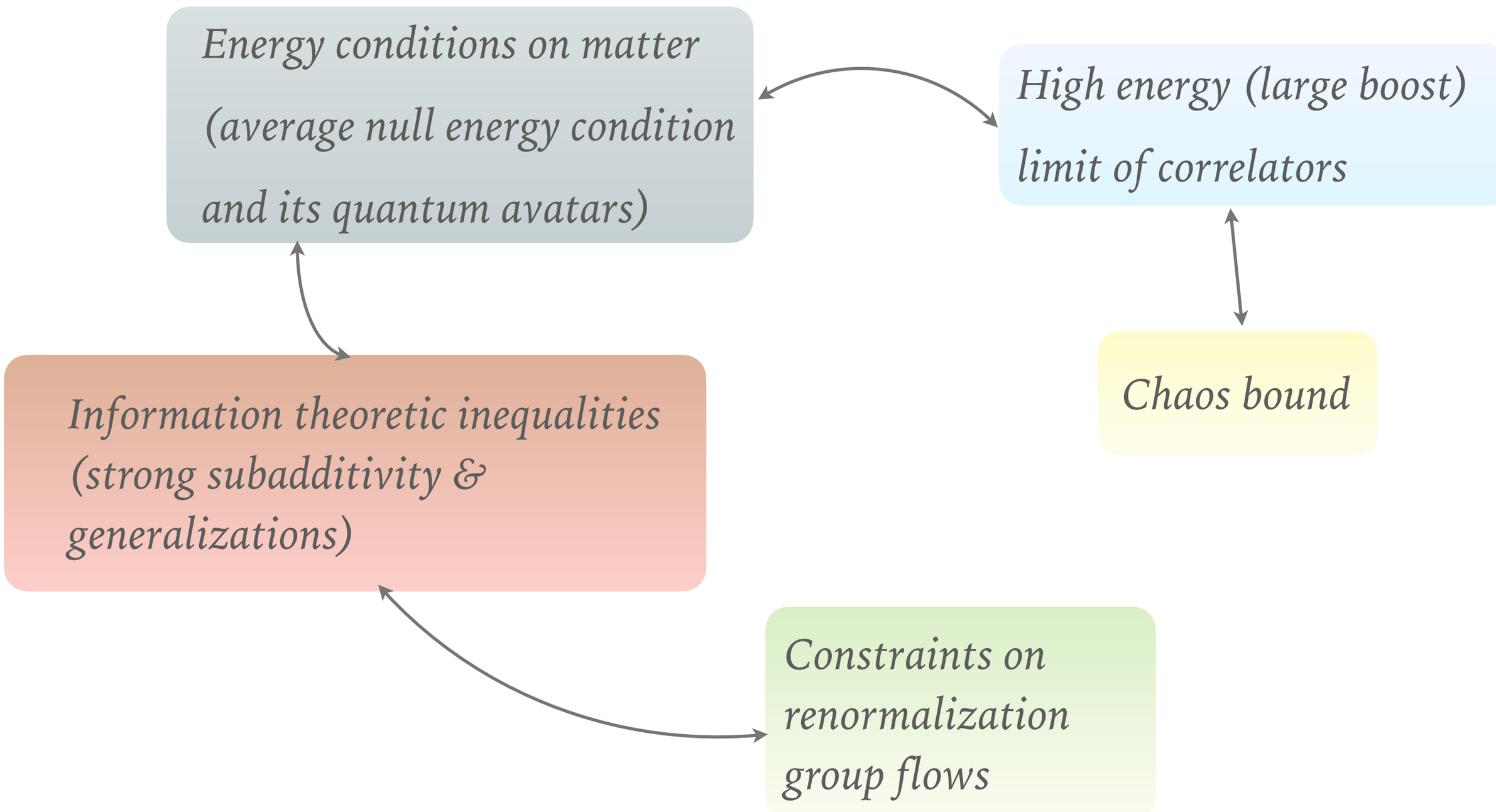
- For example: bound on transport (shear viscosity/entropy density ratio)

$$\frac{\eta}{s} > \frac{1}{4\pi} \frac{\hbar}{k_B}$$

- More robust bound on growth of out-of-time-order observables which relates to quantum chaotic dynamics:

$$\langle W(t,x)\, V(0,0)\, W(t,x)\, V(0,0)\rangle \sim C_0 - C_1\, e^{\lambda_L\,(t-t_s)}\,, \qquad \lambda_L \leq 2\pi\, k_B\, T$$

INFORMATION, UNITARITY, AND QUANTUM BOUNDS



THE HEP-QIS WISHLIST

- Develop a QI centric framework for QFT, with applications to quantum gravity

- Dynamics of information evolution in QFTs and its implications for quantum gravity (eg., black hole information)
- Information in quantum gravity beyond semiclassical regime
- Understanding the origins of geometry: how does entanglement serve as the glue that binds together bits of spacetime
- Optimizing information theoretic protocols for fast scrambling systems.
- Bounds on information: which quantum states are realizable?
- Lessons for open quantum systems…

References: QIS, QFT, and holography

Holography

1. Bombelli, Luca, Rabinder K. Koul, Joohan Lee, and Rafael D. Sorkin (1986). "A Quantum Source of Entropy for Black Holes". In: *Phys. Rev. D* 34, pp. 373–383. DOI: 10.1103/PhysRevD.34.373.
2. Srednicki, Mark (1993). "Entropy and area". In: *Phys. Rev. Lett.* 71, pp. 666–669. DOI: 10.1103/PhysRevLett.71.666. arXiv: hep-th/9303048.
3. Hooft, Gerard 't (1993). "Dimensional reduction in quantum gravity". In: *Conf. Proc. C* 930308, pp. 284–296. arXiv: gr-qc/9310026.
4. Susskind, Leonard (1995). "The World as a hologram". In: *J. Math. Phys.* 36, pp. 6377–6396. DOI: 10.1063/1.531249. arXiv: hep-th/9409089.
5. Maldacena, Juan Martin (1999). "The Large N limit of superconformal field theories and supergravity". In: *Int. J. Theor. Phys.* 38, pp. 1113–1133. DOI: 10.1023/A:1026654312961. arXiv: hep-th/9711200.

Holographic entanglement

1. Rangamani, Mukund and Tadashi Takayanagi (2017). "Holographic Entanglement Entropy". In: 931. DOI: 10.1007/978-3-319-52573-0. arXiv: 1609.01287 [hep-th].
2. Ryu, Shinsei and Tadashi Takayanagi (2006). "Holographic derivation of entanglement entropy from AdS/CFT". In: *Phys. Rev. Lett.* 96, p. 181602. DOI: 10.1103/PhysRevLett.96.181602. arXiv: hep-th/0603001.
3. Hubeny, Veronika E., Mukund Rangamani, and Tadashi Takayanagi (2007). "A Covariant holographic entanglement entropy proposal". In: *JHEP* 07, p. 062. DOI: 10.1088/1126-6708/2007/07/062. arXiv: 0705.0016 [hep-th].
4. Lewkowycz, Aitor and Juan Maldacena (2013). "Generalized gravitational entropy". In: *JHEP* 08, p. 090. DOI: 10.1007/JHEP08(2013)090. arXiv: 1304.4926 [hep-th].
5. Dong, Xi, Aitor Lewkowycz, and Mukund Rangamani (2016). "Deriving covariant holographic entanglement". In: *JHEP* 11, p. 028. DOI: 10.1007/JHEP11(2016)028. arXiv: 1607.07506 [hep-th].
6. Wall, Aron C. (2014). "Maximin Surfaces, and the Strong Subadditivity of the Covariant Holographic Entanglement Entropy". In: *Class. Quant. Grav.* 31.22, p. 225007. DOI: 10.1088/0264-9381/31/22/225007. arXiv: 1211.3494 [hep-th].
7. Engelhardt, Netta and Aron C. Wall (2015). "Quantum Extremal Surfaces: Holographic Entanglement Entropy beyond the Classical Regime". In: *JHEP* 01, p. 073. DOI: 10.1007/JHEP01(2015)073. arXiv: 1408.3203 [hep-th].
8. Faulkner, Thomas, Aitor Lewkowycz, and Juan Maldacena (2013). "Quantum corrections to holographic entanglement entropy". In: *JHEP* 11, p. 074. DOI: 10.1007/JHEP11(2013)074. arXiv: 1307.2892 [hep-th].

Geometry from entanglement

1. Lashkari, Nima, Michael B. McDermott, and Mark Van Raamsdonk (2014). "Gravitational dynamics from entanglement 'thermodynamics'". In: *JHEP* 04, p. 195. DOI: 10.1007/JHEP04(2014)195. arXiv: 1308.3716 [hep-th].
2. Faulkner, Thomas, Monica Guica, Thomas Hartman, Robert C. Myers, and Mark Van Raamsdonk (2014). "Gravitation from Entanglement in Holographic CFTs". In: *JHEP* 03, p. 051. DOI: 10.1007/JHEP03(2014)051. arXiv: 1312.7856 [hep-th].
3. Van Raamsdonk, Mark (July 2009). "Comments on quantum gravity and entanglement". In: arXiv: 0907.2939 [hep-th].

4. Maldacena, Juan and Leonard Susskind (2013). "Cool horizons for entangled black holes". In: *Fortsch. Phys.* 61, pp. 781–811. DOI: 10.1002/prop.201300020. arXiv: 1306.0533 [hep-th].
5. Czech, Bartlomiej, Joanna L. Karczmarek, Fernando Nogueira, and Mark Van Raamsdonk (2012). "The Gravity Dual of a Density Matrix". In: *Class. Quant. Grav.* 29, p. 155009. DOI: 10.1088/0264-9381/29/15/155009. arXiv: 1204.1330 [hep-th].
6. Headrick, Matthew, Veronika E. Hubeny, Albion Lawrence, and Mukund Rangamani (2014). "Causality \& holographic entanglement entropy". In: *JHEP* 12, p. 162. DOI: 10.1007/JHEP12(2014)162. arXiv: 1408.6300 [hep-th].

Error correction, bulk reconstruction

1. Almheiri, Ahmed, Xi Dong, and Daniel Harlow (2015). "Bulk Locality and Quantum Error Correction in AdS/CFT". In: *JHEP* 04, p. 163. DOI: 10.1007/JHEP04(2015)163. arXiv: 1411.7041 [hep-th].
2. Dong, Xi, Daniel Harlow, and Aron C. Wall (2016). "Reconstruction of Bulk Operators within the Entanglement Wedge in Gauge-Gravity Duality". In: *Phys. Rev. Lett.* 117.2, p. 021601. DOI: 10.1103/PhysRevLett.117.021601. arXiv: 1601.05416 [hep-th].
3. Cotler, Jordan, Patrick Hayden, Geoffrey Penington, Grant Salton, Brian Swingle, and Michael Walter (2019). "Entanglement Wedge Reconstruction via Universal Recovery Channels". In: *Phys. Rev. X* 9.3, p. 031011. DOI: 10.1103/PhysRevX.9.031011. arXiv: 1704.05839 [hep-th].
4. Jafferis, Daniel L., Aitor Lewkowycz, Juan Maldacena, and S. Josephine Suh (2016). "Relative entropy equals bulk relative entropy". In: *JHEP* 06, p. 004. DOI: 10.1007/JHEP06(2016)004. arXiv: 1512.06431 [hep-th].
5. Harlow, Daniel (2017). "The Ryu–Takayanagi Formula from Quantum Error Correction". In: *Commun. Math. Phys.* 354.3, pp. 865–912. DOI: 10.1007/s00220-017-2904-z. arXiv: 1607.03901 [hep-th].

Wormholes and teleportation

1. Maldacena, Juan and Alexey Milekhin (Aug. 2020). "Humanly traversable wormholes". In: arXiv: 2008.06618 [hep-th].
2. Maldacena, Juan, Alexey Milekhin, and Fedor Popov (July 2018). "Traversable wormholes in four dimensions". In: arXiv: 1807.04726 [hep-th].
3. Maldacena, Juan, Douglas Stanford, and Zhenbin Yang (2017). "Diving into traversable wormholes". In: *Fortsch. Phys.* 65.5, p. 1700034. DOI: 10.1002/prop.201700034. arXiv: 1704.05333 [hep-th].
4. Gao, Ping, Daniel Louis Jafferis, and Aron C. Wall (2017). "Traversable Wormholes via a Double Trace Deformation". In: *JHEP* 12, p. 151. DOI: 10.1007/JHEP12(2017)151. arXiv: 1608.05687 [hep-th].

Replica wormholes and Islands

1. Almheiri, Ahmed, Raghu Mahajan, Juan Maldacena, and Ying Zhao (2020). "The Page curve of Hawking radiation from semiclassical geometry". In: *JHEP* 03, p. 149. DOI: 10.1007/JHEP03(2020)149. arXiv: 1908.10996 [hep-th].
2. Almheiri, Ahmed, Thomas Hartman, Juan Maldacena, Edgar Shaghoulian, and Amirhossein Tajdini (2020a). "Replica Wormholes and the Entropy of Hawking Radiation". In: *JHEP* 05, p. 013. DOI: 10.1007/JHEP05(2020)013. arXiv: 1911.12333 [hep-th].
3. Penington, Geoff, Stephen H. Shenker, Douglas Stanford, and Zhenbin Yang (Nov. 2019). "Replica wormholes and the black hole interior". In: arXiv: 1911.11977 [hep-th].

4. Marolf, Donald and Henry Maxfield (2020). "Transcending the ensemble: baby universes, spacetime wormholes, and the order and disorder of black hole information". In: *JHEP* 08, p. 044. DOI: 10.1007/JHEP08(2020)044. arXiv: 2002.08950 [hep-th].
5. Almheiri, Ahmed, Thomas Hartman, Juan Maldacena, Edgar Shaghoulian, and Amirhossein Tajdini (June 2020b). "The entropy of Hawking radiation". In: arXiv: 2006.06872 [hep-th].

Quantum processing bounds

1. Maldacena, Juan, Stephen H. Shenker, and Douglas Stanford (2016). "A bound on chaos". In: *JHEP* 08, p. 106. DOI: 10.1007/JHEP08(2016)106. arXiv: 1503.01409 [hep-th].
2. Hayden, Patrick and John Preskill (2007). "Black holes as mirrors: Quantum information in random subsystems". In: *JHEP* 09, p. 120. DOI: 10.1088/1126-6708/2007/09/120. arXiv: 0708.4025 [hep-th].
3. Sekino, Yasuhiro and Leonard Susskind (2008). "Fast Scramblers". In: *JHEP* 10, p. 065. DOI: 10.1088/1126-6708/2008/10/065. arXiv: 0808.2096 [hep-th].
4. Kovtun, P., Dan T. Son, and Andrei O. Starinets (2005). "Viscosity in strongly interacting quantum field theories from black hole physics". In: *Phys. Rev. Lett.* 94, p. 111601. DOI: 10.1103/PhysRevLett.94.111601. arXiv: hep-th/0405231.

QI and QFT dymamics

1. Casini, H. and M. Huerta (2004). "A Finite entanglement entropy and the c-theorem". In: *Phys. Lett. B* 600, pp. 142–150. DOI: 10.1016/j.physletb.2004.08.072. arXiv: hep-th/0405111.
2. Casini, Horacio, Marina Huerta, Robert C. Myers, and Alexandre Yale (2015). "Mutual information and the F-theorem". In: *JHEP* 10, p. 003. DOI: 10.1007/JHEP10(2015)003. arXiv: 1506.06195 [hep-th].
3. Casini, Horacio, Eduardo Testé, and Gonzalo Torroba (2017). "Markov Property of the Conformal Field Theory Vacuum and the a Theorem". In: *Phys. Rev. Lett.* 118.26, p. 261602. DOI: 10.1103/PhysRevLett.118.261602. arXiv: 1704.01870 [hep-th].
4. Lashkari, Nima, Charles Rabideau, Philippe Sabella-Garnier, and Mark Van Raamsdonk (2015). "Inviolable energy conditions from entanglement inequalities". In: *JHEP* 06, p. 067. DOI: 10.1007/JHEP06(2015)067. arXiv: 1412.3514 [hep-th].
5. Lashkari, Nima, Jennifer Lin, Hirosi Ooguri, Bogdan Stoica, and Mark Van Raamsdonk (2016). "Gravitational positive energy theorems from information inequalities". In: *PTEP* 2016.12, p. 12C109. DOI: 10.1093/ptep/ptw139. arXiv: 1605.01075 [hep-th].
6. Balakrishnan, Srivatsan, Thomas Faulkner, Zuhair U. Khandker, and Huajia Wang (2019). "A General Proof of the Quantum Null Energy Condition". In: *JHEP* 09, p. 020. DOI: 10.1007/JHEP09(2019)020. arXiv: 1706.09432 [hep-th].
7. Hartman, Thomas, Sandipan Kundu, and Amirhossein Tajdini (2017). "Averaged Null Energy Condition from Causality". In: *JHEP* 07, p. 066. DOI: 10.1007/JHEP07(2017)066. arXiv: 1610.05308 [hep-th].
8. Hofman, Diego M., Daliang Li, David Meltzer, David Poland, and Fernando Rejon-Barrera (2016). "A Proof of the Conformal Collider Bounds". In: *JHEP* 06, p. 111. DOI: 10.1007/JHEP06(2016)111. arXiv: 1603.03771 [hep-th].
9. Hofman, Diego M. and Juan Maldacena (2008). "Conformal collider physics: Energy and charge correlations". In: *JHEP* 05, p. 012. DOI: 10.1088/1126-6708/2008/05/012. arXiv: 0803.1467 [hep-th].
10. Li, Daliang, David Meltzer, and David Poland (2017). "Conformal Bootstrap in the Regge Limit". In: *JHEP* 12, p. 013. DOI: 10.1007/JHEP12(2017)013. arXiv: 1705.03453 [hep-th].

11. Murugan, Jeff, Douglas Stanford, and Edward Witten (2017). "More on Supersymmetric and 2d Analogs of the SYK Model". In: *JHEP* 08, p. 146. DOI: 10.1007/JHEP08(2017)146. arXiv: 1706.05362 [hep-th].
12. Caron-Huot, Simon (2017). "Analyticity in Spin in Conformal Theories". In: *JHEP* 09, p. 078. DOI: 10.1007/JHEP09(2017)078. arXiv: 1703.00278 [hep-th].
13. Headrick, Matthew and Tadashi Takayanagi (2007). "A Holographic proof of the strong subadditivity of entanglement entropy". In: *Phys. Rev. D* 76, p. 106013. DOI: 10.1103/PhysRevD.76.106013. arXiv: 0704.3719 [hep-th].

Unsorted list of references grouped thematically by topic for a survey of developments in HEP-QIS applications to QFT, quantum gravity, and black holes.